RF Safety of Wires in Interventional MRI: Using a Safety Index

Christopher J. Yeung[1], Robert C. Susil[1], Ergin Atalar[2]

[1]Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD, USA
[2]Department of Radiology, Johns Hopkins University, Baltimore, MD, USA

***Abstract*- With the rapid growth of interventional MRI, radiofrequency (RF) heating at the tips of guidewires, catheters, and other wire-shaped devices has become an important safety issue. Previous studies have identified some of the variables that affect the relative magnitude of this heating but none could predict the absolute amount of heating to formulate safety margins. This study presents the first theoretical model of wire tip heating that can accurately predict its absolute value. The method of moments was used to find the induced currents on insulated and bare wires that were completely embedded in the tissue. The induced currents caused an amplification of the local specific absorption rate (SAR) distribution near the wire. This SAR gain was combined with a semi-analytic solution to the bioheat transfer equation to generate a safety index. The safety index is a measure of the worst case in vivo temperature change that can occur with the wire in place. It can be used to set limits on the spatial peak SAR of pulse sequences that are used with the interventional wire. Under worst-case conditions with resonant wires in a poorly perfused tissue, only about 100 mW/kg/°C spatial peak SAR may be used at 1.5 T. But for ≤10 cm wires with insulation thickness ≥30% of the wire radius that are placed in well perfused tissues, normal operating conditions of 4 W/kg spatial peak SAR are possible at 1.5 T. We propose a simple way to ensure safety when using an interventional wire: set a limit on the SAR of allowable pulse sequences that is a factor of a safety index below the tolerable temperature increase.**

Keywords - **MRI Safety, RF heating, interventional MRI, moment method, metallic implants**

I. Introduction

While radiofrequency (RF) heating during MRI has always been a safety concern, it has recently received greater attention with the rapid growth of interventional MRI. MRI-guided interventional procedures often involve the use of metallic devices such as surgical tools, biopsy needles, and guidewires during MR imaging. Metallic devices, even if not ferromagnetic, have the potential to interact with the electromagnetic field from the RF transmitter to cause increased RF heating near the device. This has resulted in empirical testing of a whole range of devices from surgical clamps and clips to imaging coils and vascular catheters [1].

Wire-shaped devices have gained particular attention because of the magnitude of heating that has been reported, especially with guidewires [2-5]. Extensive empirical measurements have shown that RF heating occurs primarily at the tips of wire-shaped conductive structures and is a function of the total length of the wire, the immersed length of the wire, and the position of the wire in the magnet [2-5]. While Konings et al. and Nitz et al. provided qualitative theoretical explanations for wire heating, no study has yet presented a model that can predict the amount of heating from a wire-shaped structure in order to formulate safety margins.

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The goal of this work is to present such a model. This work will demonstrate a method by which insulated and non-insulated wire structures can be numerically analyzed to calculate the maximum amount of heating that can occur with the device. The safety index is introduced as a measure of RF safety that is independent of the specific geometric configuration or type of body coil used.

II. Theory

A. RF Heating in General

RF heating in MRI is caused by the absorption of power in the imaging sample (patient). It is characterized by the specific absorption rate (SAR), given in units of W/kg. SAR can be calculated from the electric field, *E*, according to $SAR = \sigma E^2 / 2\rho_t$ [6] where σ is the electrical conductivity and ρ_t is the tissue density.

This applied power causes an increase in the tissue temperature based on the thermal characteristics of the tissue, particularly the perfusion. We have previously shown that, in the case of local RF heating in deep tissues, this heat transfer problem can be solved by convolving the SAR distribution with the Green's function of the tissue bioheat equation [7].

B. RF Heating with Conductive Wires

When a conductive wire structure is placed in the imaging sample, the electric field distribution is altered near the wire, resulting in an altered SAR distribution. We model this effect as an SAR gain. Buechler et al. [8] used a similar measure (an electric field multiplier) to report calculations of induced electric fields near metal implants due to switched gradient magnetic fields.

However, raw SAR gain by itself is not a meaningful measure of heating since bioheat transfer effects have not been accounted for. Therefore, the raw SAR gain was combined with the bioheat transfer convolution to produce a safety index. This safety index estimates the worst-case in vivo temperature increase, *ΔT*, that can occur with the wire in place for each unit of peak applied SAR, as represented in Fig. 1. It therefore helps to set limits on the peak SAR of pulse sequences that are used with the wire.

Fig. 1. The safety index relates the spatial peak applied SAR to the worst-case temperature change that can occur when using the wire in vivo. It is expressed in units of °C/(W/kg).

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Abstract

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III. METHODS

A. Calculation of SAR Gain

A numerical technique based on the method of moments [9] was used to find the induced currents on a completely embedded wire. Atlamazoglou and Uzunoglu have given a detailed description of the application of this procedure to finding induced currents and their resulting electric field distributions for both bare and insulated center-driven antennas in a homogeneous, infinite, lossy medium [10]. In their case, the driving function was non-zero only at the driving point of the antenna.

We extend their work to a passive wire situated in an incident driving electric field by making one simple change: the driving function is changed from an impulse at the center of the wire to a driving function that exists all along the wire. A uniform parallel electric field that would generate a unit applied SAR was assumed as the driving field. The raw SAR gain, then, was equal to the magnitude of the resultant total SAR from the combined incident and induced electric fields.

B. Experimental Verification

A cylindrical phantom (20 cm diameter, 60 cm length) was constructed that enabled accurate and reproducible placement of the wire and temperature measuring probes in a gel to measure SAR. The phantom consisted of a 6.5% polyacrylamide gel (EM Science, Gibbstown, NJ) doped with 0.35% sodium chloride to bring its conductivity to 0.5 S/m, a representative value for human tissue between 10 and 100 MHz [6].

Silver-plated copper hookup wire (Alpha Wire, Elizabeth, NJ) was straightened and cut into pieces ranging from 3 cm to 39 cm in 3 cm increments. Two cases were tested: 0.5 mm diameter bare wire and 0.5 mm wire with 25 μm thick insulation (polyester heat shrink tubing; Advanced Polymers, Salem, NH). Wires were centered longitudinally in the phantom and positioned at a constant radial depth of 4.5 cm in the cylindrical gel. The gel was placed in the scanner such that the cylindrical gel was coaxial with the scanner bore.

The SAR gain at both tips of each wire was measured with fiberoptic temperature probes (Fiso Technologies, Ste-Foy, Quebec, Canada - 0.05°C accuracy). Each temperature probe provided an average temperature measurement over its cylindrical sensitive region that is 8 mm long and 0.6 mm in diameter. SAR was calculated by finding the initial slope of the temperature rise (dT/dt) and multiplying by the specific heat capacity of the gel.

Experiments were performed on a GE Signa CV/i scanner. A pulse sequence optimized for high SAR deposition rather than image quality was used. Pulse sequence parameters were: fast gradient echo; 170° flip angle; and 11.4 ms TR. The estimated peak SAR given by the scanner was 4.0 W/kg. The transmit gain was increased 3 dB over the self-calibrated prescan level to double the applied power. Maximum SAR gain was computed as the ratio of the measured SAR at the tips of the wire to the SAR at the same spatial location in the gel without the wire present.

To directly compare theoretical and measured SAR gain, the theoretical SAR was spatially averaged with a thin disk to compensate for the spatial averaging caused by the temperature probes. The diameter of the averaging disk was 8 mm, equal to the length of the probe's sensitive region.

C. Calculation of the Safety Index

Once the SAR gain model was experimentally verified in the phantom experiment, the safety index was calculated to produce a meaningful measure of the intrinsic safety of a given wire. Similar to [7], raw SAR gain distributions were convolved using MATLAB (The Mathworks, Inc., Natick, MA) with the Green's function of the bioheat equation for a variety of wire types.

The safety index is the spatial maximum of the Green's function convolved SAR gain distribution (°C/(W/kg)). It was verified that this spatial maximum always occurred on the axis of the wire at the wire tip. It was therefore only necessary to compute the convolution at this single point. This could be done with a 2D calculation. SAR gain and the Green's function were sampled with increasing resolution and extent until doubling either parameter had less than a 1% effect on the final result. Thermal parameters used for the Green's function were thermal conductivity = 0.4 W/m°C and perfusion = 2.7 ml/100g/min.

IV. RESULTS

A. Experimental Verification

Fig. 2 shows an overlay of the theoretically predicted and measured SAR gain for the two test cases, accounting for the spatial averaging of the temperature probe. Good agreement between the prediction and results was achieved.

B. Safety Index

Fig. 3 shows the dependence of the calculated safety index on the insulation thickness. Increasing the insulation thickness causes the resonance to lengthen and the amplitude of that resonance to decrease. In addition, as the insulation thickness increases, the length of wire that exhibits the minimum possible safety index (wire-free case) is increased.

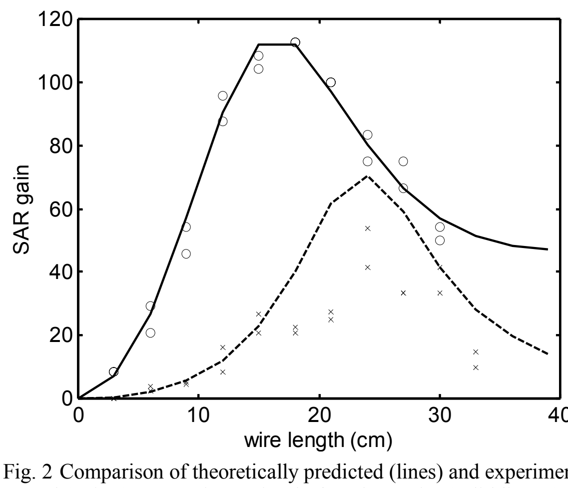

Fig. 2 Comparison of theoretically predicted (lines) and experimentally measured (points) SAR gain at wire tip for a bare wire (solid line, o) and a 10 cm insulated wire (dashed line, x). Predicted SAR gain has been averaged with a thin disk to compensate for the temperature probe's spatial averaging.

V. DISCUSSION

A. Safe Length

The concentration of RF heating at the wire tips predicted by the theoretical model, shown in Fig. 2, is in good qualitative agreement with previous observations of wire tip heating [2-5].

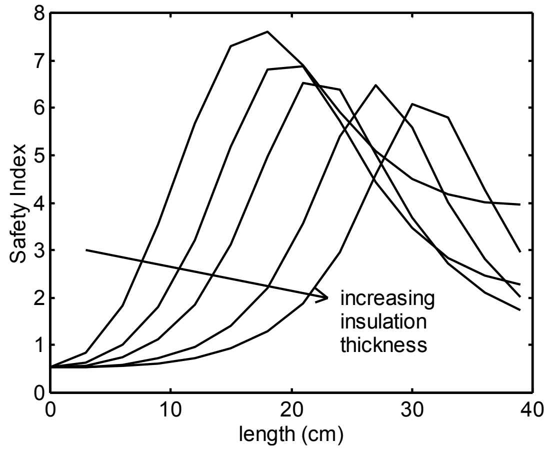

Fig. 3 Theoretically predicted safety index for varying insulation thickness (bare, 12, 25, 50, 75 μm). Safety index (°C/(W/kg) accounts for both SAR gain due to the presence of the wire and bioheat transfer. (wire diameter = 0.5 mm, tissue thermal conductivity = 0.4 W/m°C, perfusion = 2.7 ml/100g,/min, insulation relative permittivity = 3.3, tissue electrical conductivity = 0.5 S/m.)

As seen in Fig. 3, the resonance peak occurs at a length substantially less than half a wavelength[1] and is broad. In this case, the resonance occurs between 15 and 18 cm while the theoretical half wavelength is 21.5 cm. It has been assumed that wire lengths less than a quarter wavelength are generally safe [12,13]. However, for the bare wire case examined, significant SAR gain still exists at both the theoretical quarter wavelength and half the experimental resonant length. Fig. 3 suggests that wires less than 10 cm will have a markedly reduced SAR amplification only when their insulation thickness exceeds 30% of the wire radius.

B. Safety Index

The advantage of using the safety index is that it provides a measure of the safety of the interventional wire that is independent of the type of transmit coil or pulse sequence used. The worst possible absolute RF heating that can be caused by the interventional wire is the product of the spatial peak SAR generated by the pulse sequence and the safety index of the wire being used. Therefore, a simple way to ensure safety when using an interventional wire will be to place a limit on the peak SAR that is a factor of a safety index below the tolerable temperature increase.

For example, under worst-case conditions with resonant wires in a poorly perfused tissue, the safety index can be as high as about 8 °C/(W/kg). This means that if 1°C is the temperature limit, a pulse sequence with only 125 mW/kg spatial peak SAR may be used. For 10 cm or shorter wires, whose insulation thickness is at least 30% of the wire radius and are placed in well-perfused tissues, the safety index can fall below 0.25 °C/(W/kg). In this case, the whole body SAR limits dominate and normal operating conditions of 4 W/kg spatial peak SAR are permissible.

Finally, since the safety will be determined in part by the peak SAR estimated by each particular scanner, MRI system manufacturers must be precise in making these estimates.

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[1]

$$\lambda = \frac{2\pi}{\omega\sqrt{\frac{\mu\varepsilon}{2}}\sqrt{1+\left(1+\frac{\sigma^2}{\omega^2\varepsilon^2}\right)^{1/2}}} \quad [11]$$

Where λ is wavelength, ω is angular frequency, μ is tissue magnetic permeability, ε is tissue electrical permittivity, σ is tissue electrical conductivity. In experimental phantom, $\lambda = 43$ cm.

C. Future Extensions

The present work has dealt exclusively with straight wires that are completely embedded in the sample. While the method of moments theory can be extended to deal with curved wires, the analysis of partially inserted wires requires several extra degrees of complexity and may be better examined by another method. Nevertheless, many of the main insights discovered by this work are at least qualitatively applicable to such cases.

The safety index depends on a number of variables that have not yet been explicitly addressed here including wire radius, relative permittivity of the insulation, tissue electrical conductivity, perfusion, and static field strength. Furthermore, for wires longer than 40 cm, other resonance peaks may occur.

VI. Conclusion

We have demonstrated the first theoretical model of wire tip RF heating that can actually predict its absolute value and have verified its accuracy for two test cases. To formulate safety margins, we have introduced the safety index as a measure of the safety of an interventional wire that is independent of the particular MRI system with which it will be used. This safety index acts as a convenient relationship between the maximum tolerable in vivo temperature change and the spatial peak SAR of pulse sequences that will be used with the interventional wire.

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References

[1] Shellock FG. Radiofrequency energy-induced heating during MR procedures: A review. JMRI 2000; 12:30-36.

[2] Wildermuth S, Dumoulin CL, Pfammatter T, Maier SE, Hofmann E, Debatin JF. MR-guided percutaneous angioplasty: Assessment of tracking safety, catheter handling and functionality. Cardiovasc Intervent Radiol 1998; 21:404-10.

[3] Ladd ME, Quick HH, Boesiger P, McKinnon GC. RF heating of actively visualized catheters and guidewires. In Proc. ISMRM, 6th Scientific Meeting, Sydney, 1998; p. 473.

[4] Konings MK, Bartels LW, Smits HFM, Bakker CJG. Heating around intravascular guidewires by resonating RF waves. JMRI 2000; 12:79-85.

[5] Nitz WG, Oppelt A, Renz W, Manke C, Lenhart M, Link J. On the heating of linear conductive structures as guidewires and catheters in interventional MRI. JMRI 2001; 13:105-114.

[6] Polk C, Postow E. Handbook of biological effects of electromagnetic fields. 2nd ed. New York: CRC Press; 1996.

[7] Yeung CJ, Atalar E. A Green's function approach to local RF heating in interventional MRI. Med Phys 2001; 28:826-832.

[8] Buechler DN, Durney CH, Christensen DA. Calculation of electric fields induced near metal implants by magnetic resonance imaging switched-gradient magnetic fields. MRI 1997; 15:1157-66.

[9] Harrington RF. Field Computation by Moment Methods. New York: Macmillan; 1968.

[10] Atlamazoglou PE, Uzunoglu NK. A Galerkin moment method for the analysis of an insulated antenna in a dissipative dielectric medium. IEEE Trans Microwave Theory 1998; 46:988-996.

[11] Ulaby FT. Fundamentals of applied electromagnetics. 1999 ed. Upper Saddle River, NJ: Prentice-Hall; 1999. p. 279.

[12] Ladd ME, Quick HH. Reduction of resonant RF heating in intravascular catheters using coaxial chokes. MRM 2000; 43:615-9.

[13] Atalar E. Safe coaxial cables. In Proc. ISMRM, 7th Scientific Meeting, Philadelphia, 1999; p. 1006.